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RADIOMETRIC MEASUREMENTS FROM SATELLITES

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SUMMARY

Satellite radiometry is a valuable and rapidly developing tool for the study of atmospheric phenomena, as Tiros data have shown. The Nimbus spacecraft will expand measurements of the same nature as Tiros by means of greater global coverage and improved spectral and angular resolutions. Various problems peculiar to radiometric instruments are reviewed, such as the checking of calibration in orbit.

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INTRODUCTION

Conventional meteorology obtains atmospheric information mostly by *in situ* measurements. Barometric pressure, temperature, humidity, wind, cloud cover, and precipitation are recorded routinely at the surface of the earth, aloft from balloons, and occasionally from sounding rockets. In contrast to the conventional methods, satellites are confined to operating from distances of 100 or more times the thickness (about 8 km) of a homogenous atmosphere. Parameters of meteorological significance must therefore be sensed by means of electromagnetic radiation. Passive satellite radiometry operates in the spectral range of solar radiation reflected by the earth or of radiation, mostly thermal, emitted by the earth. But the inability of satellites to make *in situ* measurements must be viewed in relation to the numerous advantages that satellites provide, such as global coverage and new perspectives which are gained by observing the atmosphere from the low-density side.

EARLY METEOROLOGICAL SATELLITE EXPERIMENTS

One parameter easily measured from a satellite, and the one which most readily supports conventional observations, is the cloud cover. Therefore, it is not surprising that the first meteorological satellite, Vanguard II (1959 α), was designed to measure cloud cover[1,2] and that instruments and techniques to obtain the distribution of clouds have been perfected to a high degree in the TIROS television systems. Cloud cover cameras will also be the first experimental satellite equipment to leave the research stage and become operational.

Another experiment of a geophysical-meteorological nature, proposed originally for the IGY-Vanguard project, but first flown on Explorer VII,[3] is the heat balance experiment which measures the radiative gains and losses of energy over large areas of the earth.

Table 1 gives a list of all meteorological radiometric experiments, including television systems, which have been flown on scientific satellites of this country or which are scheduled for early Nimbus missions. Below each experiment are listed its main purpose and general information about it. In addition, the overall accuracy, spectral resolution, spatial resolution, and amount of coverage of the earth's surface are shown. Also indicated are the bandwidths required to process the information and whether or not the device can check its calibration in orbit.

Although the instruments of Vanguard II apparently performed well, useful data were not obtained[4] because an excessive wobbling motion of the satellite destroyed the proper scanning mode, which was essential to this experiment.* Explorer VII ($1959\iota_1$) data have been analyzed for nighttime segments of the orbit, and their correlation with synoptic charts has been successful.[5]

TIROS

Tiros was the next major step forward to a meteorological satellite system. More than 94,000 television pictures have been received as of this writing, and their use from a research and operational point of view has been documented by a number of papers in the scientific and popular literature.[6-9] In addition to the standard nephanalyses, Tiros pictures have revealed many other interesting phenomena, such as ice fields in the Saint Lawrence river,[10] cloud flow phenomena around islands, and man-made surface patterns.†

In both the Tiros II and III satellites ($1960\pi_1$ and $1961\rho_1$) a five-channel scanning radiometer made simultaneous measurements in five spectral regions; the principle of operation for one channel of this instrument is shown in Figure 1. The radiometer, the systems aspects of the experiment, and the physical significance of the measurements have been discussed in various publications.[11-14] Three channels measured thermal emission from the Earth in the strong water vapor bands near 6.3 μ, in the atmospheric "window" from 8 to 12 μ, and in the range from 8 to 30 μ. The two remaining channels were sensitive to reflected solar radiation, one covering almost the total range from 0.2 to 6 μ and the other from 0.55 to 0.75 μ or approximately the spectral range of the television system.

The data from the first 50 orbits of Tiros II are now available in the form of the final magnetic tape format for further analysis. Also, a volume of computer grid prints from the same 50 orbits was published last year (1961)[15,16]; it is available upon request from

*This wobbling motion is believed to have been due to a collision between the separated satellite and the third stage rocket, resulting from residual burning in the latter after separation.

†Tiros II, orbit 926, January 25, 1961, Camera 1, Frame 7. Tiros pictures are available to the public from the National Weather Records Center, Ashville, North Carolina.

Table 1

Characteristic Parameters of Satellite Meteorological Experiments

SATELLITE	EQUIPMENT	MISSION	ACCURACY	RESOLUTION		COVERAGE	CALI-BRATED IN FLIGHT	INFOR-MATION BANDWIDTH
				SPECTRAL	SPATIAL*			
Vanguard II	PbS cells	Cloud cover	Poor	Medium: .5-.8 μ	Medium: 5 mi per scan-line	Good; day only	No	Medium: 240 cps
Explorer VII	Black & white balls	Heat balance	Medium	Low	Low	Good	Indirect checks possible	Very low
Tiros I II III	1/2 inch vidicon	Cloud cover	Low	Medium: .5-.8 μ	High: 1.6-2 mi per line	Restricted by spin & storage	No	High: 62.5 kc
Tiros II III	5-chan. radiometer	Multi-purpose	Medium	Medium; 5 filters	40 mi per scan-line	Good	Zero balance only	Low: 5 x 8 cps†
	Low-res. radiometer	Heat balance	Medium	Low	Low	Restricted by spin	No	Very low: .02 cps
Tiros III	Isolated hemisph.	Heat balance	Medium	Low	Low	Good	Indirect checks possible	Very low: .1 cps
Early Nimbus	1 inch vidicon	Cloud cover (day)	Good	Medium	High: .5 mi per scan-line	Good; day only	Yes: gray edge	High
	High res. I.R. radio-meter	Cloud cover (night)	Good	Good: 3.5-4.2 μ	Good	Good; night only	Yes: zero & blackbody	Medium
	Med. res. radiometer	Multi-purpose	Good	Good; 5 filters	Medium 40 mi per line	Good	Yes: zero, blackbody, & sun	Low: 5 x 8 cps†
Later Nimbus	Electro-static tape	Cloud cover (day)	Good	Good	High	Good; day only	Yes: gray edge	High
	I.R. spectr. (Kaplan)	Temp. profile	Good	Very high; grating	Medium	Low	Yes: zero & blackbody	Low

*The resolutions quoted refer to the sub-satellite point.

†Five channels, each with 8 cps bandwidth.

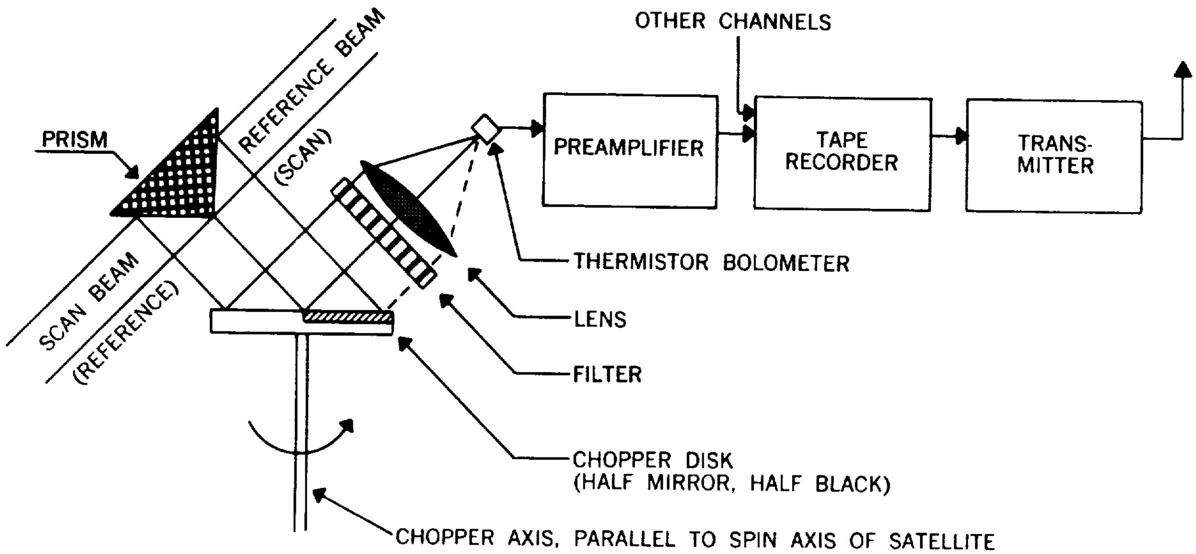

Figure 1—Functional diagram of one channel of the five-channel Tiros radiometer. The rotating disk provides chopping between the reference channel (outer space) and the earth; the scanning motion is provided by the spin of the satellite.

the Aeronomy and Meteorology Division, Goddard Space Flight Center, Greenbelt, Maryland. Samples of the maps from the Radiation Catalog are shown in Figure 2. The printed numbers correspond to radiant emittance values of a blackbody, observed through the instrument's filter, in units of 10^{-1} w/m^2. Transparent overlays (here shown superimposed on the figure) are furnished with the Radiation Data Catalog to permit coordination of the radiation data and geographical locations. Although the five-channel Tiros radiometer has shortcomings, such as critical alignment of optical components and a spectral response that deviates enough from the desired response to complicate the interpretation of data, it has nevertheless become a valuable source of data. The low resolution radiometer on Tiros II and III also produced information on the albedo and equivalent blackbody temperatures of large areas of the earth. Various studies have been made which compare radiation data to television pictures and synoptic charts,[17,18] and computer programs for more systematic studies are in preparation.

NIMBUS

The Nimbus spacecraft will carry a variety of radiometric experiments. Two scanning instruments have already reached the breadboard stage. One of them, a radiometer* with a resolution of 1/2 degree, will map thermal radiation in an atmospheric window between 3.5 and 4.2 μ. Correlation between thermal radiation in another window (8 to 12μ) and significant cloud formations has already been confirmed by the Tiros radiation experiments.[13,14]

*NASA Contract NAS 5-668, ITT, Fort Wayne, Indiana

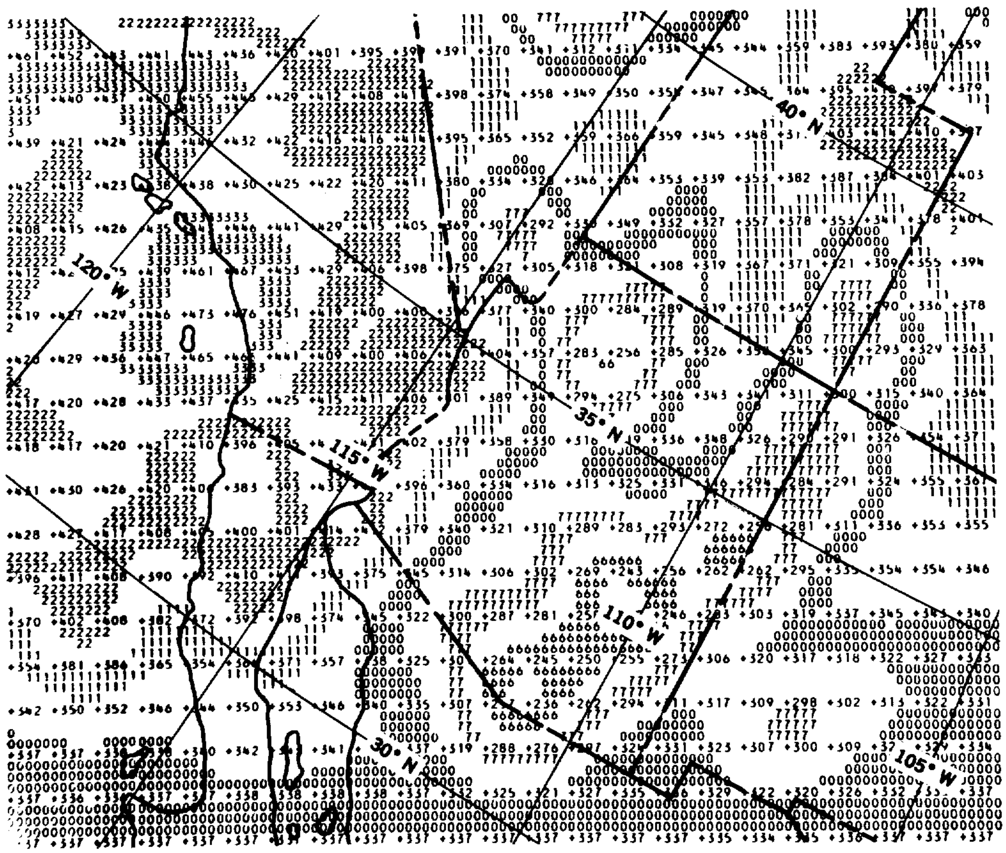

Figure 2—Sample from the Tiros II Radiation Data Catalog (Orbit 31, Channel 2, 8 - 12 microns). The numbers represent blackbody radiant emittance in units of 10^{-1} w/m^2. As many as five data points are averaged for each number shown. The overlay (here superimposed) allows correlation between data points and geographical locations. The contours of the southwestern United States and northern Mexico are shown.

It must be remembered however that infrared methods, which discriminate between clouds and surface by a difference in apparent radiation temperature, will not always recognize low level clouds, whose temperatures may be close to that of the background.

In contrast to Tiros, in which the scanning motion was provided by the spin of the satellite, the Nimbus radiometers have to generate the scan internally; this is done by a rotating mirror tilted at 45 degrees to its drive axis (Figure 3). The scan lines are perpendicular to the satellite's velocity vector and provide complete coverage of the earth from horizon to horizon without overlap or gaps in the scan pattern at the sub-satellite point. The use of the atmospheric window from 3.5 to 4.2 μ made the application of fast semi-conductive detectors possible without imposing excessive cooling requirements. In the satellite, a radiative cooling system maintains a detector temperature of approximately -80°C, which is sufficient since lead selenide cells cooled to -80°C show detectivities D*

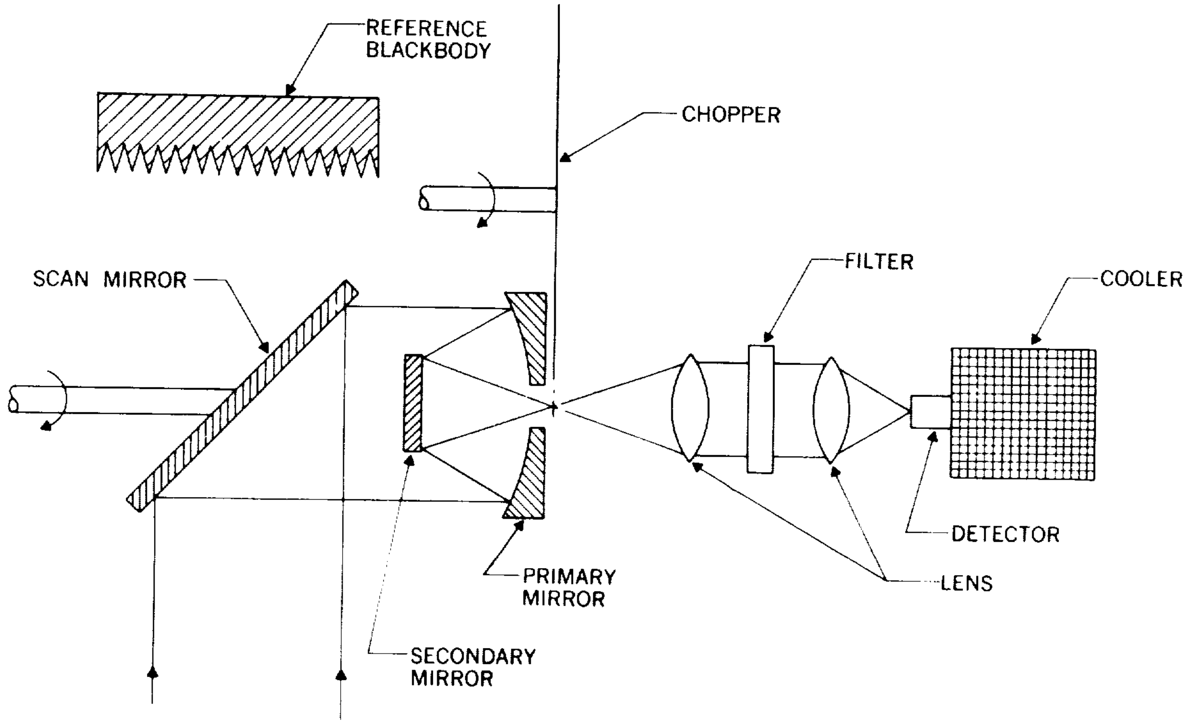

Figure 3—High Resolution Radiometer for Nimbus. This instrument measures thermal radiation in the 3.5-4.2 atmospheric window. Its main purpose is the mapping of the Earth's cloud cover during the night. The scan mirror and chopper are driven by the same motor.

of 10^{10} cm/w-cps$^{1/2}$. The cooler, a surface of high emissivity 2 1/2 x 4 cm in size, is thermally in contact with the cell but isolated from the spacecraft, exposed to outer space but never to the sun. This is possible on Nimbus because the orientation of the spacecraft is actively controlled with respect to the earth and the sun. Absolute radiation temperatures measured by the high resolution radiometer will be accurate to ±2.5°C and will allow crude estimates of the altitudes of clouds.

The medium resolution radiometer* (Figure 4) to be flown on Nimbus is a continuation of the Tiros five-channel radiation experiment. Early versons of this instrument will have about the same wavelength ranges as the Tiros radiometer, but with some improvements. The spectral range of the 8 - 12μ channel will be narrowed to a 1μ band—from 10 to 11μ approximately, where the window is most transparent—to avoid the ozone bands and to minimize residual absorption by water vapor. The spectral responses of other channels have also been improved.

The major advancement, however, is in a check of calibration during operation in space. Both the medium and the high resolution radiometer will scan outer space (the zero reference level for all channels) twice each revolution of the scan mirror. Once during each revolution the scan mirror faces the radiometer structure, which has been converted

*NASA Contract NAS 5-757, Santa Barbara Research Center, California

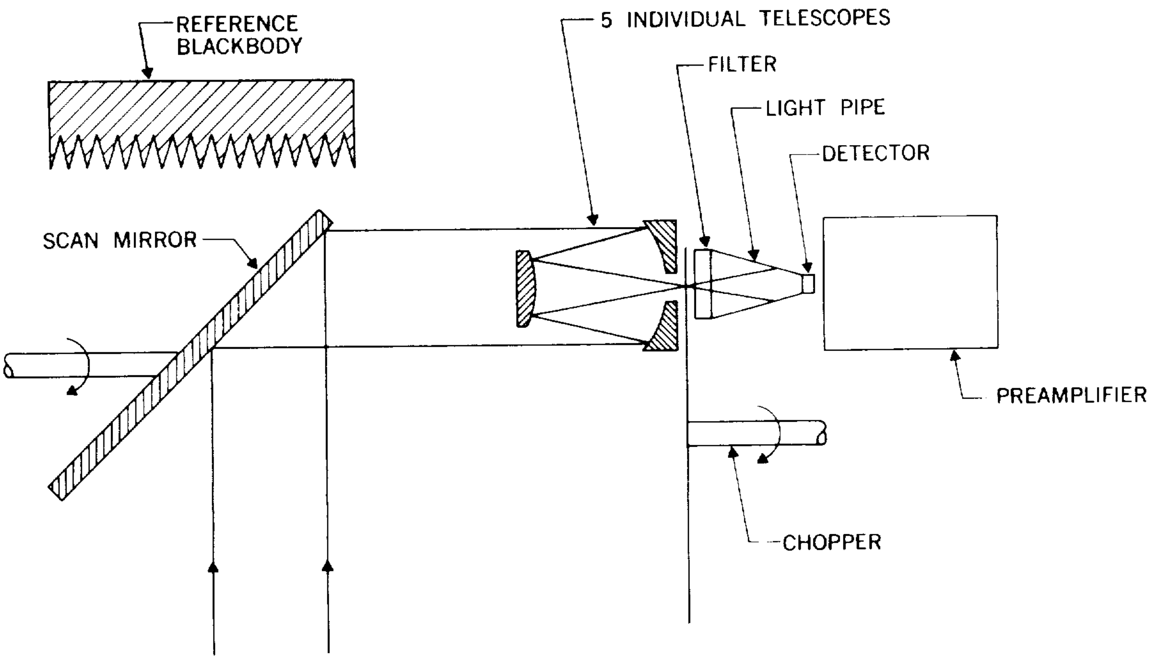

Figure 4—Medium Resolution Radiometer for Nimbus. This instrument maps the earth at five different wavelengths. The temperature of a blackbody for in-flight-calibration is telemetered independently.

into a blackbody by deep grooves and a proper coating, and which has a separate telemetering channel to monitor its temperature. Two points on the calibration curve are available for all thermal (infrared) channels—zero and a point near the maximum of the dynamic range. However, some channels which are insensitive to infrared, such as the 0.25 to 4 μ channel of the medium resolution radiometer, require other means of checking the calibration. Here, the sun provides the calibration signal. Twice in each orbit the lower surface of Nimbus is exposed to sunlight, this condition occurring just before and after the spacecraft enters and leaves the earth's penumbra. A metal reflector and a sapphire bead then channel sunlight into the field of view of the radiometer. The reference signal is generated only for a short period of time each orbit. This check of calibration for all channels of both radiometers is achieved without additional moving parts.

In the Tiros radiation experiment only the zero reference level was available as a check point, and a drift has been observed in some cases. In Tiros II, channel 1, (6.3 μ) deteriorated rapidly after orbit 600 and in other channels a similar condition was observed. Some of these effects, discussed in the Tiros II Radiation Data Users' Manual[15,16], have been explained; others are not completely understood. The check of calibration during flight operation permits the experimenter to make corrections in the data if a small change has occurred or, of equal importance, proves that the instrument has not changed its performance.

FUTURE EXPERIMENTS FOR NIMBUS

A number of experiments are in preparation which are to be flown in later Nimbus missions. One is an electrostatic tape camera[19] which combines the function of a television system and a tape recorder within one unit.* The erasable film stores light intensities in the form of electrostatic charges. In a manner similar to that of the television system planned for the early Nimbus mission, a gray scale is transmitted with each frame and will allow light level measurements in a radiometric sense. Ultimately, if this technique is developed into a reliable instrument, it may replace the standard television cameras as well as their associated recorders in the satellite.

The radiometric experiments described above treat the atmosphere as a two-dimensional surface. Only crude estimates can be made about the vertical structure, such as the temperature and humidity. In the literature two techniques have been described to obtain the temperature profile of the atmosphere from a satellite. The first, suggested by King[20], requires the measurement of the angular distribution of the specific intensity from the atmosphere (limb darkening). A fairly wide spectral range in which thermal emission originating from an atmospheric constituent of uniform mixing ratio, for example CO_2, is suitable for this method. The second technique, suggested by Kaplan[21], requires observations with high spectral resolution. An instrument based on this second technique is presently under construction.† Then, if we have the temperature profile, similar techniques in a water vapor band can yield, at least theoretically, the humidity distribution in the atmosphere. But to obtain the temperature profile is a very difficult task. All techniques based on the infrared emission of gases suffer to some extent by the presence of high clouds. However, passive microwave radiometers which can penetrate cloud layers may in the future support infrared devices.

Another experiment, the measurement of the upper height of clouds, together with a temperature measurement in an atmospheric window, yields a point of the temperature profile. In addition to its value to meteorologists, this information on cloud heights is of direct importance to pilots. One technique for measuring this cloud height is based on the absorption of sunlight by an atmospheric gas of constant mixing ratio,[22,23] such as CO_2 or O_2. The ratio of back-scattered radiation in an absorption band to radiation in a nearby window varies strongly with the altitude of the back-scattering surface, and hence can be used to determine the altitude. Another technique, suggested by Coulson,[24] uses the scattering properties of the free atmosphere above the cloud and requires measurements in the ultraviolet as well as in the near infrared.

*NASA Contract NAS 5-434, RCA, A.E.D., Princeton, New Jersey
†U.S.W.B. Contract CWB 9868, Barnes Engineering Company, Stanford, Connecticut

Some of the suggestions mentioned in this brief review, as well as others not covered here, will eventually evolve into radiometric instruments to be placed on meteorological satellites. Accurate radiometry is difficult even under laboratory conditions and even more so at a remote location in the unfamiliar and often hostile environment of space. However, methods, instruments, and techniques will certainly evolve and improve to permit continued advancement of our investigations of the atmosphere.

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